INDIRECT MEASUREMENTS OF ATMOSPHERIC TEMPERATURE PROFILES FROM SATELLITES:

V. ATMOSPHERIC SOUNDINGS FROM INFRARED SPECTROMETER MEASUREMENTS AT THE GROUND

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ABSTRACT

The vertical downward spectral radiances for eight spectral intervals in the 15-μ CO_2 band were measured with a spectrometer having a resolution of 5 cm.$^{-1}$ This experiment was designed to be similar to the proposed experiment in which a satellite-borne spectrometer will measure the vertical upward spectral radiance of the atmosphere. The purpose of each experiment is to determine the temperature distribution in the earth's atmosphere as a function of pressure.

The observations were obtained with an IR–7 spectrometer. The mathematical problem of inverting an integral equation for the case of measurements made from the ground is the same as that for satellite and balloon observations. The data and resulting temperature distributions are shown. The agreement between actual and deduced soundings is reasonably good near the ground, but deteriorates with height, as expected.

1. INTRODUCTION

The preceding series of papers [5, 6, 8, 10] have dealt with an introduction to the problem of atmospheric temperature determination by means of a satellite-borne spectrometer and the theoretical method of obtaining a solution of the radiative transfer equation

$$\frac{I(\nu_i,0)-\beta(\nu_i)}{\alpha(\nu_i)}=-\int_0^{t_0}B[\nu_R,\,T(t)]\frac{d\tau(\nu_i,t)}{dt}\,dt, \qquad i=1,2,\ldots,8 \tag{1}$$

which is reproduced from Wark and Fleming [10], and therefore the meaning of the symbols is not repeated here. It has been pointed out [10] that when experimental data with relatively small errors are used in equation (1), the errors in the resulting solution can be enormously large. This observation was clearly demonstrated [5] when the "breadboard" model of the satellite infrared spectrometer was used to sound the atmosphere from the ground to provide experimental data for preliminary analyses. During those experiments, however, the satellite spectrometer incorporated only four frequency channels. The question arose of whether more accuracy could be obtained by increasing the number of channels from four to eight in the 15-μ CO_2 band. Twomey [8] discussed this problem theoretically. In this experiment an attempt was made to resolve this question by sounding the atmosphere from the ground with a Beckman Model IR–7 spectrometer in eight selected spectral intervals. Furthermore, the transmittances could be easily measured with the IR–7 spectrometer at the same resolution, thereby eliminating slit-function errors.

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2. MEASUREMENT OF DOWNWARD SPECTRAL RADIANCE

The spectrometer response was calibrated as a function of spectral radiance with two blackbodies [5]. The block diagram for calibration and observation is shown in figure 1. The reference blackbody, R, was maintained at 0° C.; the temperature of the second blackbody, C, was varied from −20° to 20° C. in 5° C. increments. For each temperature, spectral radiances were recorded for eight frequencies, whose band centers are 667.5, 677.5, 688.5, 694.5, 702.5, 712.5, 727.5, and 747.5 cm.$^{-1}$; the spectrometer resolution was 5 cm.$^{-1}$ at 670 cm.$^{-1}$, with a geometrically fixed slit width. A chopper placed between the two

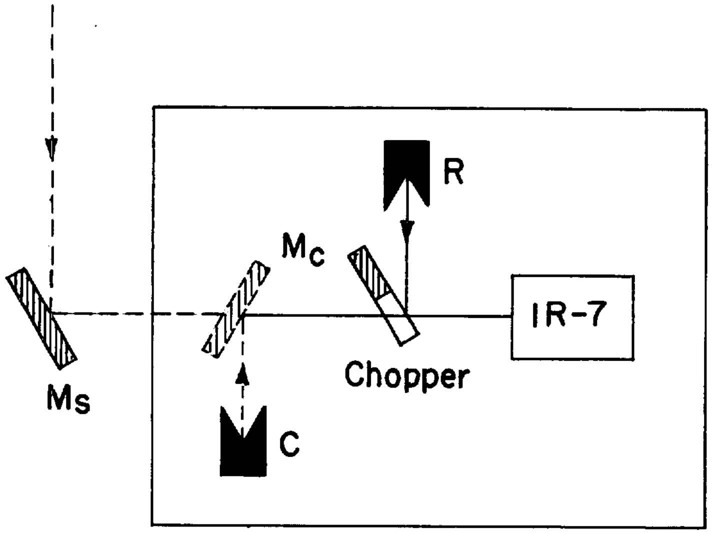

FIGURE 1.—Block diagram of the equipment used for measurement of downward radiance and calibration of the spectrometer (IR-7). R=reference blackbody, C=second blackbody, M_c=first mirror, M_s=second mirror.

blackbodies allowed the difference of the spectral radiances of the two blackbodies to be recorded. A graphical analysis revealed a linear relationship between the response, s, and the difference of the spectral radiances

$$B_C(\nu_i)-B_R(\nu_i)=m(\nu_i)s, \qquad i=1, 2, 3, \ldots, 8 \qquad (2)$$

where B_C and B_R are the spectral radiances from the blackbodies C and R, respectively, and $m(\nu_i)$ is the constant of proportionality for the i-th spectral interval.

During the observations, the first mirror, M_c, was removed, so the instrument detected the sky radiance by way of the second mirror, M_s (in reference [5] these are M23 and M24, respectively). The instrument was purged with nitrogen, and a thermocouple was placed on the mirror to monitor its surface temperature; two additional thermocouples located at 5 m. and 17.7 m. above the mirror gave temperatures of the air near the surface. These temperatures were used to establish the lowest portion of the temperature soundings, and were supplemented by the radiosondes launched during the observation periods from nearby Sterling, Va., elevation 82.8 m.

The atmospheric sounding experiments were performed at Suitland, Md., elevation 86.7 m., at 1140 GMT September 21 and 0740 GMT September 22, 1962.

3. TRANSMITTANCE

Absorption spectra in the 15-μ CO_2 band were obtained with the spectrometer at the same resolution used for the atmospheric spectral radiance measurements. The absorption cell was of the variable-path-length type (10 cm. to 10 m. in six increments). Nitrogen was admitted as a line broadening agent, which has essentially the same effect as dry air. Both the partial pressure of CO_2 and that of N_2 were varied to yield total pressures of 1.0, 0.1, and 0.01 atmospheres.

The transmittances in the band exhibit appreciable pressure and temperature dependences. As a result, the measured transmittances as a function of pressure were augmented with theoretical data [7] for temperature dependence. The U.S. Standard Atmosphere [9], 1962, was assumed as an approximation to the actual temperature conditions in calculating the transmittances.

Figure 2 shows the transmittances in each of the eight spectral intervals versus the optical path length, u, of carbon dioxide. The broken lines represent the values for an isothermal and isobaric atmosphere at 313° K. and 1000 mb. The optical path length, u, of atmospheric carbon dioxide is related to a pressure level, p, by

$$u=248\frac{p_0-p}{p_0} \text{ (cm.-atm.)} \qquad (3)$$

where p_0 is the surface pressure, and the total path of 248 cm.-atm. results from the assumption that the carbon dioxide is uniformly mixed with a ratio of 0.031 percent by volume.

In a stratified atmosphere, the transmittance of carbon dioxide depends upon an "effective" pressure over the optical path. In an isothermal atmosphere, the effective pressure related to the corresponding optical thickness is expressed by

$$\bar{p}(u)=\frac{1}{u}\int_0^u pdu=\frac{1}{2}(p_0-p). \qquad (4)$$

The solid lines in figure 2 are the transmittances, obtained from equation (4) and the laboratory data at varied pressure. Corrections for temperature were made following the procedures given in [7], using the U.S. Standard Atmosphere, 1962 [9]. The dotted lines in figure 2 are the transmittances resulting from modifications of the isobaric data for both stratification and temperature.

4. RESULTS

From equation (1), using the transmittances in figure 2 and the known temperature sounding, the corresponding spectral radiances have been calculated for the two observational times. Table 1 compares the observed radiances with the calculated sets

The observed and calculated radiances agree fairly well at 667.5, 677.5, 688.5, 694.5, and 702.5 cm.$^{-1}$ However, the calculated radiances are significantly lower than the observed in the remaining spectral intervals. These discrepancies between the observed and calculated radiances are systematic; they increase in the regions of decreasing absorption by carbon dioxide. It seems likely that this

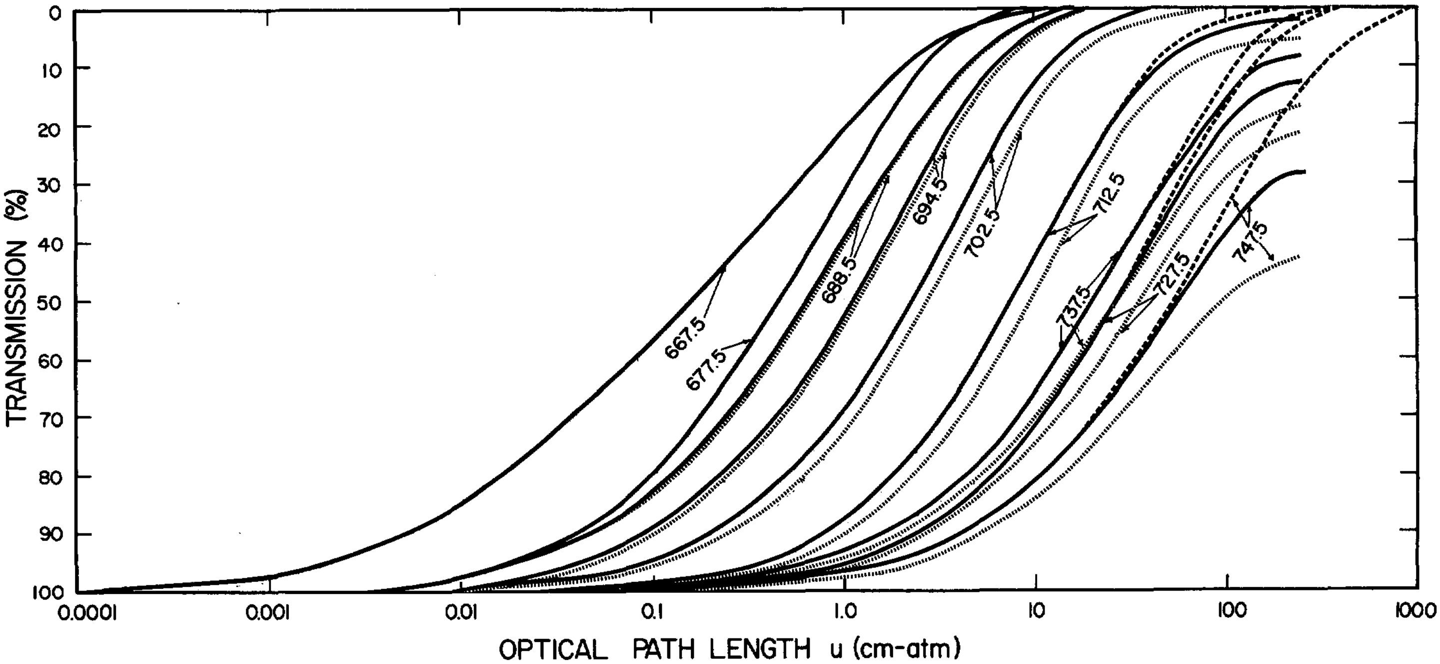

FIGURE 2.—Transmittances versus path length u in the 15-μ carbon dioxide band. The broken lines show transmittances at $T=313°$ K. and $p=1000$ mb. The solid lines are the transmittances corrected for pressure in the stratified atmosphere. The dotted lines show the transmittances adjusted for both pressure and temperature (U.S. Standard Atmosphere, 1962). The 737.5 cm.$^{-1}$ interval was discarded because of redundance.

effect results from ignoring the absorption by the water vapor band which overlaps the carbon dioxide band.

The transmittance by the atmosphere, including both carbon dioxide and water vapor, can be approximated very closely by

$$\tau(\nu_i,p)=\tau_{CO_2}(\nu_i,p)\cdot\tau^{l}_{H_2O}(\nu_i,p)\cdot\tau^{c}_{H_2O}(\nu_i,p) \qquad (5)$$

TABLE 1.—*Observed and calculated radiances for two observational times; (a) 1140* GMT, *September 21, 1962; (b) 0740* GMT, *September 22, 1962*

ν (cm.$^{-1}$)	Radiances {erg/(cm.^{2} sec. steradian cm.$^{-1}$)}					
	(a)			(b)		
	Observed	Calculated From τ (CO_2)	Calculated From τ [(CO_2)+(H_2O)]	Observed	Calculated From τ (CO_2)	Calculated From τ [(CO_2)+(H_2O)]
667.5	117.17	118.92	118.92	121.87	121.94	121.94
677.5	116.13	117.68	117.68	120.18	121.05	121.05
688.5	115.33	116.57	116.56	118.94	119.90	119.90
694.5	115.01	115.92	115.90	118.76	119.26	119.26
702.5	113.73	114.56	114.65	117.73	117.78	117.91
712.5	106.32	104.76	107.04	111.53	107.84	110.85
727.5	88.26	80.72	87.27	94.85	83.38	92.20
747.5	64.22	56.54	65.51	72.72	58.46	70.76

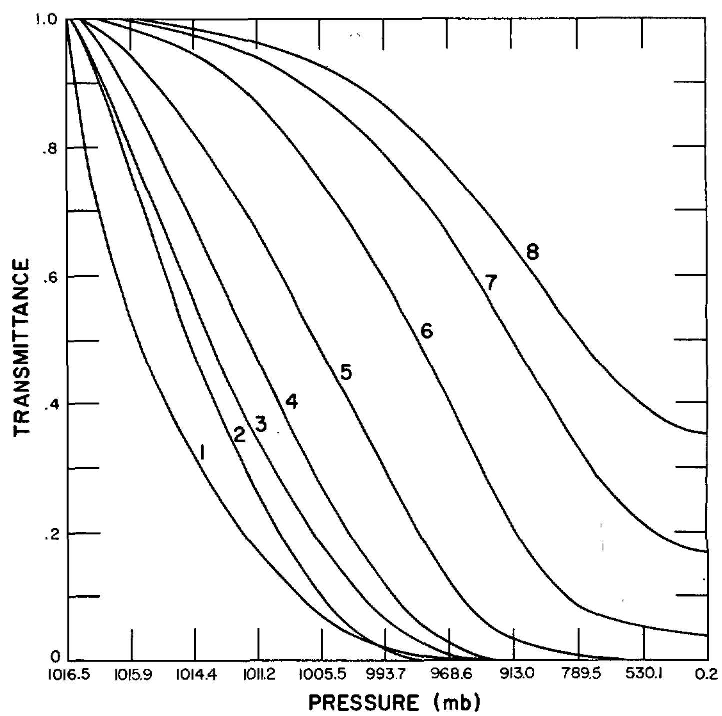

FIGURE 3.—Transmittances for a synthetic atmosphere, including the effects of both carbon dioxide and water vapor, versus the nonlinear pressure scale described in the text.

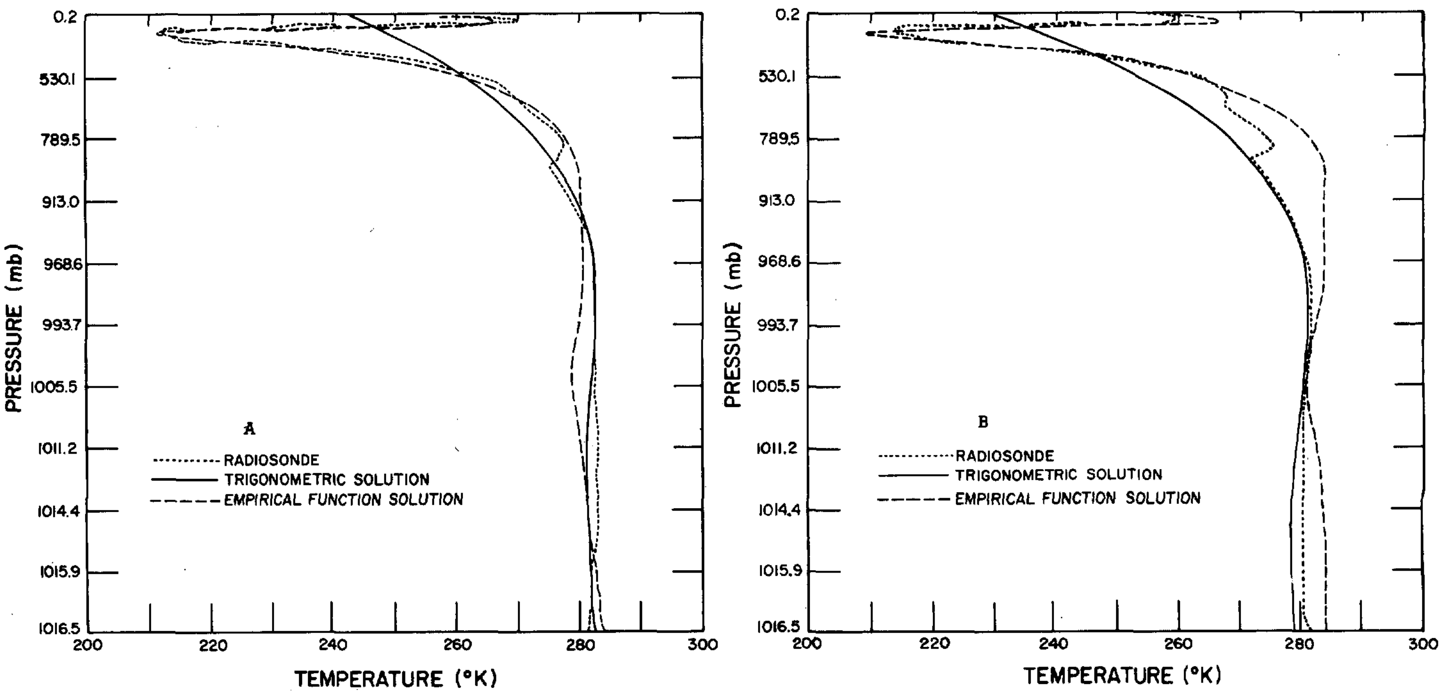

FIGURE 4.—Solutions to the inverse problem for Suitland, Md., at (a) 1140 GMT, September 21, 1962, and (b) 0740 GMT, September 22, 1962. The dotted lines indicate the observed soundings taken by radiosondes at Sterling, Va. and local air temperatures near the surface at Suitland, Md. The dashed lines represent solutions using empirical orthogonal functions, and the solid lines represent solutions using trigonometric functions.

where τ_{CO_2} is the transmittance by carbon dioxide alone, $\tau^l_{H_2O}$ is the transmittance by the lines of water vapor within the spectral interval, and $\tau^c_{H_2O}$ is the corresponding transmittance for the continuum. In calculating the water vapor transmittances, the Sterling, Va., radiosonde data were used. The Curtis-Godson [2, 3] approximation and Godson's [4] formulation of the transmittance by lines of random intensities and positions were used to calculate $\tau^l_{H_2O}$; a 5 cm.$^{-1}$ triangular slit function was used as a weighting mechanism in the latter. The results of Bignell et al. [1] were applied to calculate $\tau^c_{H_2O}$. The resulting transmittances are shown in figure 3; the pressure scale is approximately logarithmic in the difference between the surface pressure and any level p [i.e., log (p_0-p)]. The set of spectral radiances based on these transmittances is listed in table 1; these values compare favorably with the observed values.

It is obvious that the use of the water vapor distribution of the very sounding one is trying to reconstruct is self-defeating, unless an independent means is found to obtain this information. However, since the essential purpose of this experiment was to observe and analyze the effects of increased channel data by comparison with the similar experiment [6] using four channels, it was felt that the question of determination of water vapor could be subordinated.

Having established a reliable set of transmittances, the observed data given in table 1 were used in equation (1) to derive the temperature profiles. The method used is that given by Wark and Fleming [10]. For comparative purposes, two solutions were obtained: expansion of the indicial function in (1) into a trigonometric series, and a similar expansion into a series of empirical functions. The trigonometric expansion included eight terms, whereas the expansion into empirical functions was confined to four terms; the complete set of eight radiances was used in each solution. Figures 4a and 4b show these results.

It is clear that the trigonometric solution most closely approximates the observed sounding up to about 850 mb. On the other hand, the solution based on empirical functions is superior above that level; this agreement, however, has little meaning because the information content of the curves in figure 3 is minimal above that level. Most significant is the fact that neither method detected the presence of the inversion above 850 mb.

By the method of Twomey [8], the four measurements corresponding to the transmittance curves numbered 1, 4, 6, 8 in figure 3 were found to be independent up to their r.m.s. error. The measurements from these four spectral intervals were employed in (1), with the indicial function expressed as the first four terms of the empirical function expansion. The resulting profiles were comparable in quality with the solutions using eight channels. Thus, although the latter solutions were slightly superior, the addition of four measurements contributed only in a least squares sense.

5. DISCUSSION

Sounding the atmosphere from below by the method described herein raises questions that may be resolved only by further research. It was found, for instance, that significant energy was contributed by the overlapping water vapor bands. Recognition of this fact during the course of this experiment forced inclusion of these bands in the computations.

The slopes of the transmittance curves in figure 3, which are weighting functions in the radiative transfer equation (1), are so distributed as to cause a rapid attrition of the information content. This attrition is most rapid at the inversion levels, where statistical support, as expressed in the empirical functions, is critical. Therefore, the major portion of the information supplied by the spectrometer measurements is confined to the lowest part of the atmosphere. Because the sample set used here was too homogeneous, the solutions suffered from the fact that they deviated widely from the mean of the sample set. At the other extreme, an excessively heterogeneous sample would yield an improved overall profile at the expense of structural detail. An objective method to select an optimum set somewhere between the two is indicated.

As originally conceived, this experiment was to concern itself exclusively with atmospheric carbon dioxide and its spectral characteristics as they relate to the reconstruction of a temperature profile, using the observations from a ground-based spectrometer. It appears that productive application of this technique would require observations in the water vapor bands as well as in the carbon dioxide band; the number of independent data for the temperature profile is no more than four, and possibly fewer; and a careful consideration of the generation of empirical functions and their relation to the transmittances is necessary.

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